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Hot Electron Generation and Transport Using Kα Emission

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Abstract. We have conducted experiments on both the Vulcan and Titan laser facilities to study hot electron generation and transport in the context of fast ignition. Cu wires attached to Al cones were used to investigate the effect on coupling efficiency of plasma surround and the pre-formed plasma inside the cone. We found that with thin cones 15% of laser energy is coupled to the 40μm diameter wire emulating a 40μm fast ignition spot. Thick cone walls, simulating plasma in fast ignition, reduce coupling by x4. An increase of pre-pulse level inside the cone by a factor of 50 reduces coupling by a factor of 3.

1. Introduction

In the fast ignition scheme to inertial confinement fusion, a high intensity short pulse laser is used to generate fast electrons. These energetic electrons propagate to the dense core and deposit their energy in a small spot igniting the fuel. Critical to the success of fast ignition is how efficiently the short pulse laser energy is converted to fast electrons. Substantial work has been carried out regarding conversion efficiency in flat targets [1,2] To date, only four relatively small "proof of concept" integrated fast ignition experiments have been reported in the literature reported [3-4] and only one dealt with details of fast electron transport and conversion efficiency [5]. Larger scale integrated fast ignition experiments will be carried out in the near future on OmegaEP, FIREX, and NIF ARC. However, experiments on relatively small-scale lasers can still provide valuable information relevant to fast ignition, provided that the targets are designed carefully. For example, wires attached to cones provide a simplified geometry to study most of the aspect of electron generation and transport. When laser-generated electrons leave the tip of the cone, they enter the wire. Their flux, mean energy, and conversion efficiency can be determined from Kα emission they induce in the wire. Moreover, a wire with 40μm cross-sectional area, the same size as the required fast ignition spot, allows us to study the forward-directed electrons that are more likely to make it to the fast ignition spot.

In this paper, we report on conversion efficiency experiments conducted with cone-wire targets using Kα emission as a diagnostic. We discuss the consequences of neglecting electron refluxing on the interpretation of Kα emission.

2. Experimental setup and diagnostics

Our experiments were conducted on two laser facilities: the Vulcan laser at Rutherford Appleton Laboratory and the Titan laser at Lawrence Livermore National Laboratory. In the Vulcan experiment, the targets were 1 mm long 40 μm thick Cu wires attached to Al cones with 12μm wall thickness [Fig.1-a]. They were irradiated with 350J of laser energy delivered in 1ps and focused to a peak intensity of 2x10^{20} W/cm^2 with an f/3 off-axis parabola. An x-ray imager and x-ray spectrometer, with 30° and 50° viewing angles respectively with respect to the cone-wire axis, were used to collect Kα emission from the wires. In the Titan experiments, the cone wall thickness was varied from 12μm to 160μm and the wires were similar to the ones used in Vulcan. The laser energy was 150J delivered in 0.7ps with 50% of the energy contained in 15μm diameter spot. An improved Kα imager, which uses an optimized assembly of collimators and magnets to increase signal-to-noise ratio, was used get high-resolution spatially resolved information [Fig.1-b]. A newly developed highly ordered pyrolythic graphite spectrometer (DCHOPG) [6] was used to get the number of photons induced by fast electrons propagating through the wires. The viewing angles with respect to the cone-wire axis of the Kα imager and DCHOPG were 43° and 18° respectively.

3. Results and discussions

In the cone-wire experiments two quantities are measured: the absolute number of Cu Kα photons induced by fast electrons and the slope of Kα emission along the wire. To determine laser-to-electron conversion efficiency and the mean energy of fast electrons, we have used a numerical transport model [7]. This model includes binary collisions, electric fields, and temperature dependent resistivity. We first inject a distribution of electrons with a given total energy and given fast electron temperature. Then a Kα emission profile is numerically generated along the wire. This is a two parameter fit where we seek a combination of electron total energy and temperature that gives a good fit to the experimental data [Fig.2].

The Vulcan data shows that 15% of laser energy is converted to fast electrons [8]. The electron beam temperature is 750 keV, which is much lower than the value predicted by ponderomotive scaling at 2x10^{20} W/cm^2. This could be a consequence of density steepening, seen in PIC simulations, at high laser intensities [9]. Our transport model neglects the transport through the cone tip and the effect of magnetic fields. LSP modeling of cone wire targets is underway. The 15% conversion efficiency to 40μm wire, emulating the 40μm fast ignition spot, is encouraging. However, these results are obtained with thin-walled cones. In real fast ignition experiments, the cone is embedded in plasma surround, which provides a path for the electrons that are generated at wide angles to escape. To study this effect we have used Al cones with variable wall thickness (12, 25, and 160μm). The absolute Kα emission, recorded with DCHOPG, is plotted as function of cone wall thickness in Fig 3-a. This data shows that increasing cone wall thickness by a factor of 12 reduces Kα emission in the wire by a factor of 4.

This due to the fact that hot electron density close to the tip of the cone is higher for thin cones compared to the thick ones (Fig 3-b). In the case of thick cones, electrons that are generated with wide angles are lost to the wall and do not make it to the wire. In the case of thin cones, sideways electrons are trapped in the wall due to electrostatic sheaths. Some of them will eventually make it the wire and contribute to Kα emission. This means that electron refluxing in thin cones enhances coupling to the wire and the coupling is not simply due to forward-directed source electrons. Since electron refluxing may not occur in real fast ignition targets with plasma surround, it is very important to take refluxing into account when inferring coupling efficiencies using thin cones. Experiments with 10μm Al/30μm Cu (refluxing flat target) and 10μm Al/30μm Cu/1000μm Al (non-refluxing flat target) show that refluxing enhances Kα emission by a factor of 5.

Fast ignition lasers may have hundreds of mili-joules in pre-pulse and the pre-formed plasma may have a detrimental effect on conversion efficiency. Work by Baton et al. [10] with 1ω vs. 2ω indicate significantly reduced coupling with pre-pulse. We have conducted experiments with non-refluxing thick walled cones attached to wires and we varied the amount of pre-pulse from 8 mJ to 400 mJ. Kα emission data from the wire show that an increase of pre-pulse by a factor of 50 reduces the coupling to the wire by a factor of 3. In term of conversion efficiency, this data indicate that 400mJ of pre-pulse together with surrounding plasma may reduce the coupling to the wire to ~ 1%. Work by MacPhee et al. [11] shows details of electron generation inside the cone. At a pre-pulse level of 100 mJ, hot electrons are generated further away from the cone tip and are accelerated at wide angles toward the walls. Due to pre-formed plasma, the laser undergoes filamentation and self-focusing far away from the tip of the cone.

In conclusion, experiments with cone-wire targets show that electron refluxing in thin cones enhances coupling to the wire and the coupling is not simply due to forward-directed source electrons. Refluxing is unlikely to occur in integrated FI experiments due to the plasma surround. Therefore, the coupling efficiency obtained with thin cones has to be considered an upper limit. It has been shown here that the addition of controlled pre-pulse reduces the coupling efficiency. Further experiments are needed to optimize energy transfer, particularly the trade off between increased energy absorption in the coronal plasma with larger density scalelengths and beam filamentation in the extended region between the critical density and the ablation front. The results presented here indicate that prepulses with energies < 10mJ may be required for full-scale FI lasers. However, these experiments were done with laser parameters (150 J and 0.7 ps) that are different from those required for FI. Extending this study to higher laser energies and longer pulse-length is an additional but necessary step for both experiments and simulations

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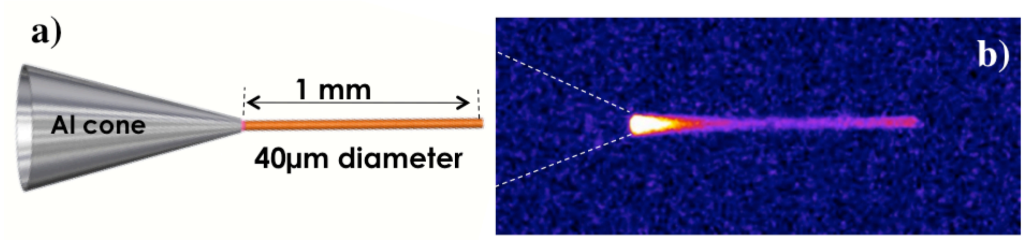

Fig.1: cone-wire target (a); Typical Cu Kα image from Titan experiment (b)

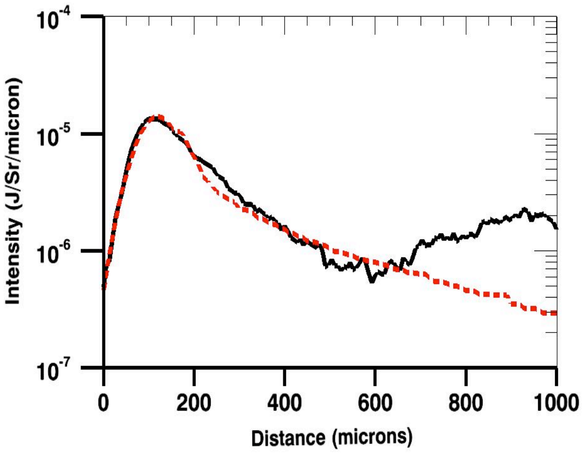

Fig.2: black line- experimental profile; red line- modelled profile

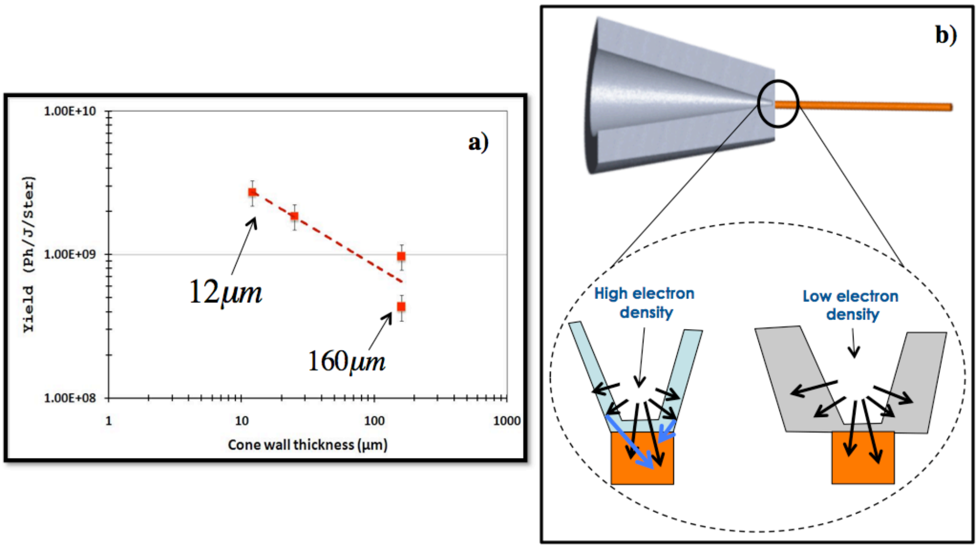

Fig.3: Cu Kα emission from the wire as a function of cone wall thickness (a); cartoon showing electron behaviour inside the cone for the two cases of thin and thick cones (b)